Convectively-Driven Mean Flow in Partially Enclosed Seas.

P.I.: Tony Maxworthy
Dept. of Aerospace and Mechanical Engineering
University of Southern California
Los Angeles
CA 90089-1191

Grant No.: N00014-97-1-0671.
Web Site: http://ae-www.usc.edu/rsg/gfd/mix/mixing.html

LONG-TERM GOALS

The goal of the project is to gain an understanding of the density and velocity fields created by a surface forcing, e.g., buoyancy flux and wind stress, in partially enclosed seas with hydraulically constrained exits. Applications to the Red and Mediterranean Seas are foremost in our thinking but the flows in fjords and other embayments of this type are also of interest.

OBJECTIVES

We wish to determine the scaling laws that relate the density and velocity distributions to the independent variables in the problem. The latter would include the magnitude of the buoyancy flux and wind stress and the geometry of the sea and the exit strait. Hopefully these should then lead to a more complete understanding of the prototype and to suggestions for suitable field experiments.

APPROACH

In order to understand the problem outlined above we have built a small-scale laboratory model (*2.5 m* long) that simulates most of the conditions encountered in the natural system. This model is then operated under a wide range of operating conditions of buoyancy flux and model geometry so as to gain a complete understanding of both the scaling laws and the physical mechanisms that are important in this system.

WORK COMPLETED

The effects of buoyancy flux and a simple strait geometry have been completed (see below). The latter consisted of a simple sill with or without a lateral contraction. We have also run a number of tests with a contraction alone. We have also looked at the effects of extra, mechanical, mixing in the main channel in order to try to understand the conditions required to reach the “overmixed” state of Stommel and Farmer (1953). Also we started to look into strait geometries where two displaced constraints are present while each of them can consist of a sill and/or lateral contraction.

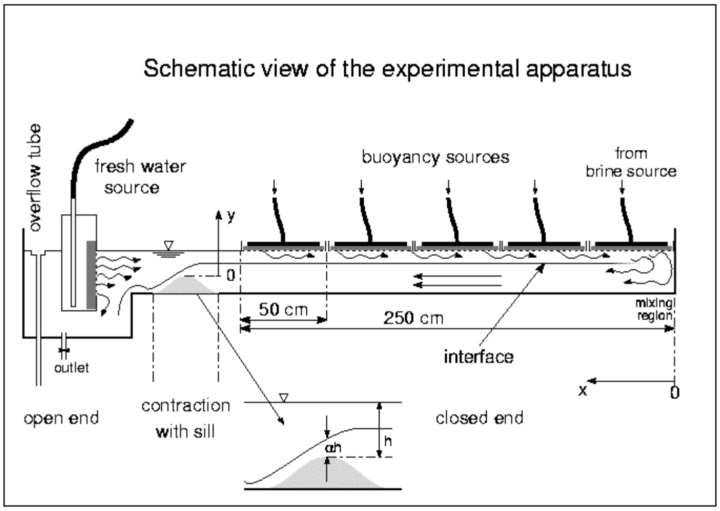
RESULTS

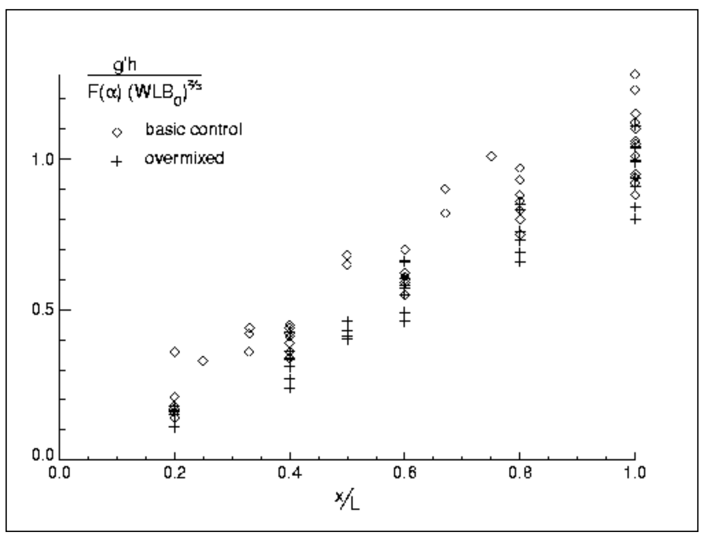
Single Contraction Experiments

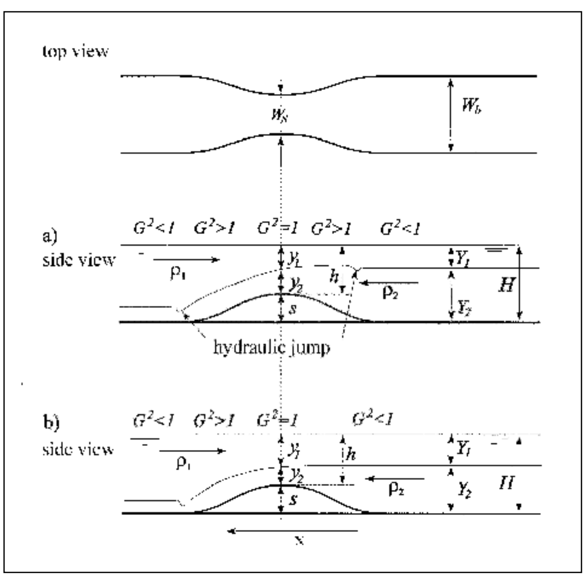
By means of a long channel, experiments are conducted to investigate the influence of the geometry of the strait and the channel as well as the magnitude of the buoyancy flux. Two different scaling laws, one by Phillips (1966), and one by Maxworthy (1994, 1997a, 1997b) are compared with the experimental results. The experiments suggest a scaling law for the distribution of the buoyancy flux, which is linear along the axis of the channel and first, was suggested by Maxworthy, rather than proportional to a power of 2/3, which was suggested by Phillips. This result holds for the experimental results and appears to be valid for a number of natural systems (i.e. Red Sea, Mediterranean Sea). The experimental facility consists of a long channel that is some *3 m* long, *20.5 cm* wide and *20 cm* deep.

The suggested scaling should read like $g' = kB_0^{2/3}xh^{-4/3}$ where k is a proportionality constant depending on geometric and dynamic properties of the flow. B_0 is the buoyancy forcing, x is the longitudinal direction and h the total depth of the water above the sill crest. The factor k has the form $k = F(\alpha)W^{2/3}\lambda^{-1/3}$, where $F(\alpha)$ is a u-shaped function depending on the non-dimensional interface depth α above the sill crest with a minimum of 2.52 for $\alpha = 0.5$ and which goes to infinity for $\alpha = 0$ and 1, W is the ratio between the width of the channel W_b and the width of the sill W_s, and λ is the ratio between the length of the channel L and the water depth h.

Applying this scaling law to all of the experiments, which were conducted for different values of W and varying values of λ, for each W, a very good agreement is observed.







The hydraulic control condition is crucial to this investigation. Two kinds of controls are considered, one we call *basic control* and the other *overmixed*. For the basic control case, only the side of the sill towards the open end of the channel is hydraulically separated from the flow conditions through the contraction and $\alpha < 0.5$. In the overmixed case both sides of the sill are hydraulically separated from the fluid reservoirs and $\alpha = 0.5$.

In the figure G^2 is the composite Froude number of the two fluid layers as defined in Lawrence (1990) or Armi (1986), for example. A flow region with Froude number $G^2 = 1$ represents a super critical flow and serves to hydraulically separate the subcritical flow regions ($G^2 < 1$).
From our experiments it was found, that for basic control conditions (*bc*) the proportionality constant is $k = 1.04$ while for the overmixed flow (*om*) $k = 2.62\ W^{2/3}\lambda^{-1/3}$.

A given system can be evaluated to whether it is overmixed or not by defining the ratio $r = g'_{omc}/g'_{bc} = 2.52\ W^{2/3}\lambda^{-1/3}$, which only depends on geometric quantities. A value of $r > 1$ identifies a flow which is overmixed.

To prove this a set of experiments with mechanical mixing at various locations along the channel were conducted.

Single Contraction with Mechanical Mixing

The physical setup for these experiments is the same as in the former experiments except that a rotating mixer is used to force turbulent mixing between the inflowing and outflowing fluid layers. The rate of mixing is controlled by the RPM of the mixer and the location is varied $x = 50\ cm$ and $x = L$.

The results suggest that $g'(L)$ indeed is independent of the specifics of the mixing within the channel. Different rates from weak to very strong mixing do not effect $g'(L)$ which is especially true for mixing locations $x < L - 50\ cm$. For example for a genuinely non-overmixed channel the interface shows strong turbulent mixing between the location of the mixing device and $x = 0\ cm$. This observation is backed by $g'(x) \sim x^{2/3}$ which is the appropriate scaling for this case and this part of the channel. Within the remainder of the channel from the mixing location to $x = L$, g' adjusts so that $g'(L)$ takes on a value according to the basic control case.

Moving the location of mechanical mixing very close to the contraction location ($x = L$) generates disturbances that effect the flow conditions across the contraction. Thus it is not clear yet whether it is possible at all to force a system that by default is basic hydraulic control to become overmixed.

Dual Contraction Experiments

In natural systems in general the shallowest and narrowest section of a strait do not coincide as assumed in the experiments above. Therefore a set of experiments was conducted where two contraction sections some distance apart were employed. The geometrical properties for both contractions have to be such that neither of them generates overmixed conditions in order to observe a feedback between the two.

The experiments conducted so far include a sill with no lateral contraction as the outer most contraction towards the open end of the channel ($i = 1$). The second contraction ($i=2$) located between the first contraction and the buoyancy sources. This consisted of different width ratios W_2 for the lateral contraction while the sill height s_2 was varied from $s_2 = 0$ to $s_2 > s_1$.

The scaling function $g'(L)$ seems to be according to the one found earlier for the basic control case except with an extra factor $k = W_2^{2/3}$. The value of h to be chosen is the smaller one derived from $h = H - s_{1,2}$.

The underlying physical process and the theoretical derivation need yet to be completely identified. Theoretical descriptions of width changes in a single layer open channel flow incorporate the factor of $W^{2/3}$ (Woodward, 1951). The effort is under way to identify the processes for a two-layer exchange flow with width changes as well.

IMPACT/APPLICATIONS

As noted above the laboratory model appears to support the claim that the surface-to-depth density difference has a linear dependence with distance from the closed end of the sea. This is consistent with existing measurements during some portion of the seasonal cycle. Also, the model shows the importance of intense mixing at the closed end of the sea and the details of the hydraulic flow at the narrow/shallow strait. These observations need to be tested during a field program that can use the experimental results to concentrate on a few, well-chosen locations for detailed measurement rather than try to survey the whole sea at low spatial resolution.

REFERENCES

Armi, 1986, “The hydraulics of two flowing layers with different densities”, J. Fluid Mech., **163**

Lawrence, 1990, “On the hydraulics of Boussinesq and non-Boussinesq two-layer flows”, J. Fluid Mech., **215**

Maxworthy**,** T., 1994, “Mixing in partially-enclosed seas”, Ocean Mod. **105**

Maxworthy**,** T., 1997a, “Frictionally and hydraulically constrained model of the convectively-driven meanflow in partially-enclosed seas”, Deep Sea Res., **44**

Maxworthy**,** T., 1997b, Ann. Rev. Fluid Mech. **29**,

Phillips, O.M., 1966, On turbulent convection currents and the circulation of the Red Sea in early summer”, Deep Sea Res., **13**

Stommel, H. and Farmer, H.G., 1953, “Control of Salinity in an Estuary by a Transition,” J. Mar. Res., 230, 13-20.

Woodward, Sherman M. 1951. Hydraulics of Steady Flow in Open Channels, 5th ed.

PUBLICATIONS:

Grimm, T., 1998, “*Dichteinduzierte Strömungen in einem langen Kanal*”, PhD Thesis, Bericht ***4***, MaxPlanck-Institut für Strömungsforschung, Göttingen, Germany.

Grimm, T. and Maxworthy, T., 1998, Experiments on the Buoyancy-Driven Mean-Flow in a Long Channel. Ocean Modelling, **116**

Grimm, T. and Maxworthy, T., 1998, “Buoyancy-Driven Mean-flow in a Long Channel with a Hydraulically-Constrained Exit Condition,” subm. to J. Fluid Mechs. (Preprint available).